Course Title: **Radiological Control Technician**
Module Title: **Interaction of Radiation with Matter**
Module Number: **1.07**

Objectives:

1.07.01 Identify the definitions of the following terms:
- a. ionization
- b. excitation
- c. bremsstrahlung

1.07.02 Identify the definitions of the following terms:
- a. specific ionization
- b. linear energy transfer (LET)
- c. stopping power
- d. range
- e. W-value

1.07.03 Identify the two major mechanisms of energy transfer for alpha particulate radiation.

1.07.04 Identify the three major mechanisms of energy transfer for beta particulate radiation.

1.07.05 Identify the three major mechanisms by which gamma photon radiation interacts with matter.

1.07.06 Identify the four main categories of neutrons as they are classified by kinetic energy for interaction in tissue.

1.07.07 Identify three possible results of neutron capture for slow neutrons.

1.07.08 Identify elastic and inelastic scattering interactions for fast neutrons.

1.07.09 Identify the characteristics of materials best suited to shield:
- a. alpha
- b. beta
- c. gamma
- d. neutron radiations

INTRODUCTION

All radiation possesses energy, either inherently (electromagnetic radiation) or as kinetic energy of motion (particulate radiations). The interaction of radiation with matter transfers some or all of this energy to atoms of the medium through which the radiation is passing. To say that radiation interacts with matter is to say that it is either scattered or absorbed. The mechanisms of energy transfer for radiation are of fundamental interest in the field of radiological health for the following reasons:

- Deposition of energy in body tissues may result in physiological injury.
- The products of interactions are used in radiation detection systems.
- The degree of absorption or type of interaction is a primary factor in determining shielding requirements.

References:

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; Pacific Radiation Press; 1994.
2. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago.
3. "Radiological Health Handbook"; Bureau of Radiological Health; U. S. Department of Health, Education, and Welfare; Washington, D.C.; 1970.
4. "The Health Physics and Radiological Health Handbook"; Edited by Bernard Shleien; Scint, inc., Silver Spring, MD.; 1992.

TRANSFER OF ENERGY MECHANISMS

1.07.01 Identify the definitions of the following terms:
a. ionization
b. excitation
c. bremsstrahlung

The transfer of energy from the emitted particle or photon to atoms of the absorbing material may occur by several mechanisms but, of the radiations commonly encountered, the following three are the most important:

Ionization

Ionization is any process which results in the removal of a bound electron (negative charge) from an electrically neutral atom or molecule by adding enough energy to the electron to overcome its binding energy. This leaves the atom or molecule with a net positive charge. The result is the creation of an ion pair made up of the negatively charged electron and the positively charged atom or molecule. A molecule may remain intact or break-up, depending on whether an electron that is crucial to molecular bonds is affected by the event.

Figure 1 below schematically shows an ionizing particle freeing an L shell electron.

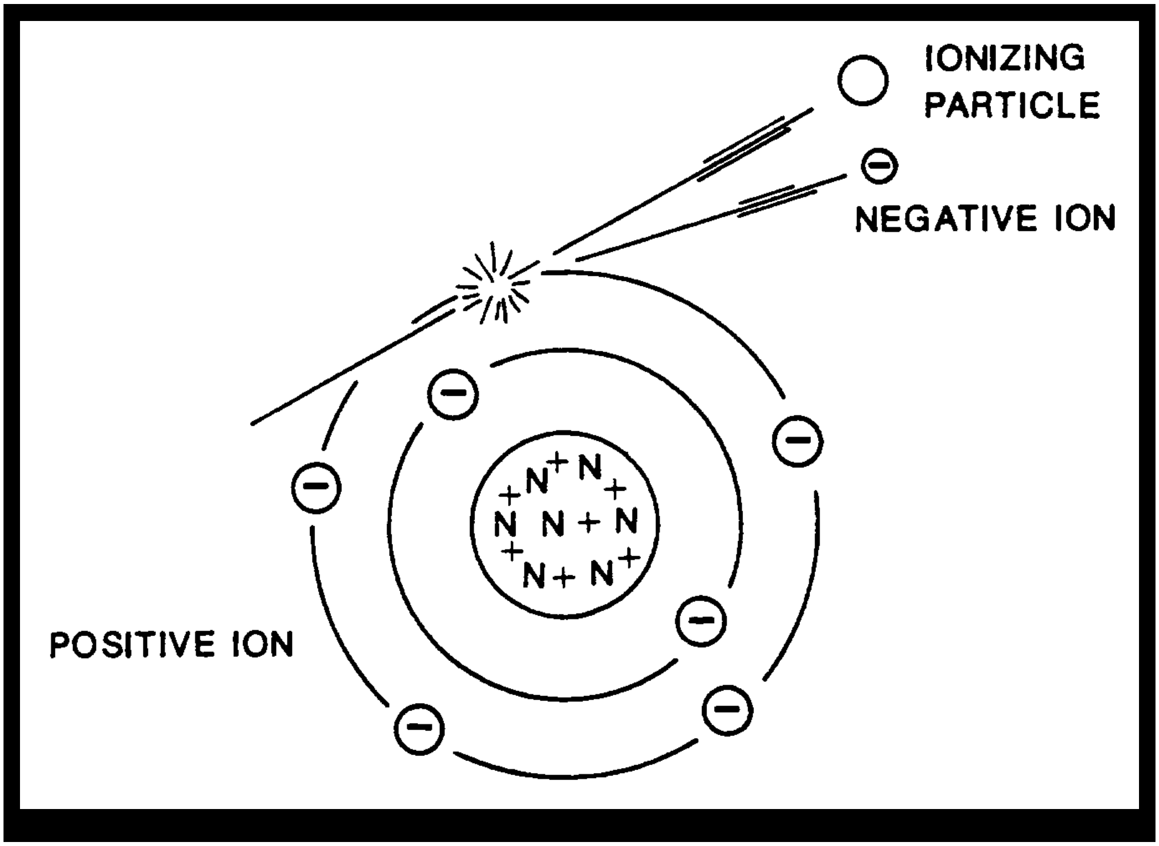

Figure 1 - Ionization

Excitation

Electron excitation is any process that adds enough energy to an electron of an atom or molecule so that it occupies a higher energy state (smaller binding energy) than its lowest bound energy state (ground state). The electron remains bound to the atom or molecule, but depending on its role in the bonds of the molecule, molecular break-up may occur. No ions are produced and the atom remains electrically neutral. Figure 2 below schematically shows an alpha particle (2 protons and 2 neutrons) exciting an electron from the K shell to the L shell because of the attractive electric force (assuming there was a vacant position available in the L shell).

Nuclear Excitation is any process that adds energy to a nucleon in the nucleus of an atom so that it occupies a higher energy state (smaller binding energy). The nucleus continues to have the same number of nucleons and can continue in its same chemical environment

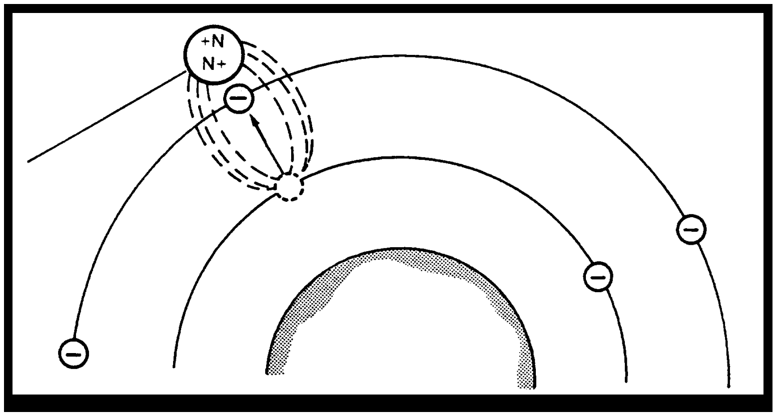

Figure 2 -Electron Excitation

Bremsstrahlung

Bremsstrahlung is the radiative energy loss of moving charged particles as they interact with the matter through which they are moving. Significant bremsstrahlung results from the interaction of a high speed charged particle with the nucleus of an atom (positive charge) via the electric force field. In the case of a negatively charged electron, the attractive force slows down the electron, deflecting it from its original path. The kinetic energy that the particle loses is emitted as a photon (called an x-ray because it is created outside the nucleus). Bremsstralung has also been referred to as "braking radiation", "white radiation", and "general radiation". Bremsstrahlung production is enhanced with high Z materials (larger coulomb forces) and high energy electrons (more interactions occur before all energy is lost).

Ordinarily, the atoms in a material are electrically neutral, i.e., they have exactly as many negative electrons in orbits as there are positive protons in the nucleus. Thus, the difference, or net electrical charge, is zero. Radiations have the ability to either free one or more of the electrons from their bound orbits (ionization) or raise the orbital electrons to a higher energy level (excitation). After ionization, an atom with an excess of positive charge and a free electron are created. After excitation, the excited atom will eventually lose its excess energy when an electron in a higher energy shell falls into the lower energy vacancy created in the excitation process. When this occurs, the excess energy is liberated as a photon of electromagnetic radiation (x-ray) which may escape from the material but usually undergoes other absorptive processes locally.

Nuclei also have various possible energy states of the nucleons above the ground or lowest bound energy state. The nucleus can be excited but nuclear excitation occurs only for neutrons or other radiations of relatively high energies. Following nuclear excitation analogous to atomic electron excitation above, the nucleus will eventually return to the ground state and release the excess energy in photons of electromagnetic radiation (gamma rays).

DIRECTLY IONIZING RADIATION

Charged particles do not require physical contact with atoms to interact with them. The "Coulomb force" (force from the electrical charge) will act over a distance to cause ionization and excitation in the absorber medium. Particles with charge (such as alpha and beta) that lose energy in this way are called directly ionizing radiation. The strength of this force depends on:

- Energy (speed) of the particle
- Charge of the particle
- Density and atomic number (number of protons) of the absorber.

The "Coulomb force" for even a singly charged particle (an electron) is significant over distances greater than atomic dimensions (remember this is the same force that holds the electrons in bound energy states about the nucleus). Therefore, for all but very low physical density materials, the loss of kinetic energy for even an electron is continuous because the "Coulomb force" is constantly "pushing" on electrons of at least one atom and possibly many atoms at the same time.

1.07.02 Identify the definitions of the following terms:
a. specific ionization
b. linear energy transfer (LET)
c. stopping power
d. range
e. W-value

Specific Ionization

As a charged particle passes through an absorber, the energy loss can be measured several ways. One method used is specific ionization. Specific ionization is the number of ion pairs formed by the particle per unit path length and is often used when the energy loss is continuous and constant such as with beta particles (electrons) or alpha particles. The number of ion pairs produced is dependent on the type of ionizing particle and the material being ionized. For example, an alpha particle traveling through air has a specific ionization of 80,000 ion pairs per cm of travel. A beta particle has a specific ionization of about 5,000 ion pairs per cm of travel in air. Specific ionization is a macroscopic quantity that accounts for all energy losses that occur before an ion pair is produced.

Linear Energy Transfer

Another measure of energy deposited in an absorber by a charged particle is the Linear Energy Transfer (LET). The LET is the average energy locally deposited in an absorber resulting from a charged particle per unit distance of travel (keV/cm). The LET is therefore a measure of the local concentration of energy per path length resulting from ionization effects. Biological damage from radiation results from ionization; therefore, the LET is used for determining quality factors in the calculation of dose equivalent.

Stopping Power

Stopping power of an absorber is its ability to remove energy from a beam of charged particles. Stopping power is measured as the average energy lost by a charged particle per unit distanced travelled (keV/cm). Stopping power and LET may have the same units but are not equal because, although ionization may occur and removes energy from the beam, not all of that energy gets deposited locally and so does not contribute to LET. In other words, LET $\leq$ stopping power because some electron ions may interact via Bremsstrahlung or excitation and the resulting photons escape the local area. Materials having higher stopping power values cause the particle to lose its energy over shorter distances.

Range

Inversely related to the stopping power of the absorber is the range of the charged particle. The concept of range only has meaning for charged particles whose energy is kinetic energy which is lost continuously along their path. The range of a charged particle in an absorber is the average depth of penetration of the charged particle into the absorber before it loses all its kinetic energy and stops. If a particle has a high range, the absorber has a low stopping power. If the particle has a short range, the absorber has a high stopping power.

W-Value

Specific Ionization, Linear Energy Transfer, Stopping Power, and Range can all be related to each other if one knows the average amount of energy needed to ionize a material. The average amount of energy needed to create an ion pair in a given medium is called the W-Value for the medium. Table 1 below summarizes the terms used in describing the energy losses from radiations in matter.

Table 1. Summary of Energy Loss Terms and Units

Term	Abbr.	Definition	Units
W-value	W	the average amount of energy needed to produce an ion pair in a given medium	eV/ion pair
Specific ionization	S.I.	(average number of) ion pairs produced (by a charged particle) per unit distance traveled in an absorbing medium	ion pairs/cm
Linear Energy Transfer	LET	(average value of) energy locally deposited (by a charged particle) in an absorbing medium per unit distance	keV/cm
Range	R	average distance traveled by a radiation in an absorbing medium	cm
Stopping Power	S	for a given absorber, the average energy lost by a charged particle per unit distance traveled	keV/cm

ALPHA ABSORPTION

An alpha particle is made up of two protons (positively charged) and two neutrons, all strongly bound together by nuclear forces. If such a particle approaches an electron (negatively charged), it experiences a strong electrostatic attraction, whereas if it approaches an atomic nucleus (also positively charged) it will tend to be repelled. Alpha particles have a mass about 8,000 times that of an electron. They are ejected from the nuclei of radioactive atoms with velocities of the order of 1/20 the speed of light. All of these properties--its large mass, its charge, and its high velocity tend to make the alpha particle an efficient projectile when it encounters atoms of an absorbing material. In other words, it would have a high probability of interacting, or colliding, with orbital electrons, and also atomic nuclei.

When speaking of "collisions" between subatomic particles, it should be understood that the particles (for example an alpha and an electron) need approach each other only sufficiently close for Coulomb forces to interact. Such an interaction may then be referred to as a collision.

Figure 3 below schematically shows such a collision, resulting in ionization. In this case, the kinetic energy of the alpha particle is decreased and shows up as a free electron with kinetic energy. The free electron's kinetic energy is less than the alpha energy loss by the amount of energy necessary to free the electron (its binding energy). Because the alpha particle is so much more massive than the electron, the alpha particle typically only loses a small fraction of its energy in any collision and travels in a relatively straight path through the material.

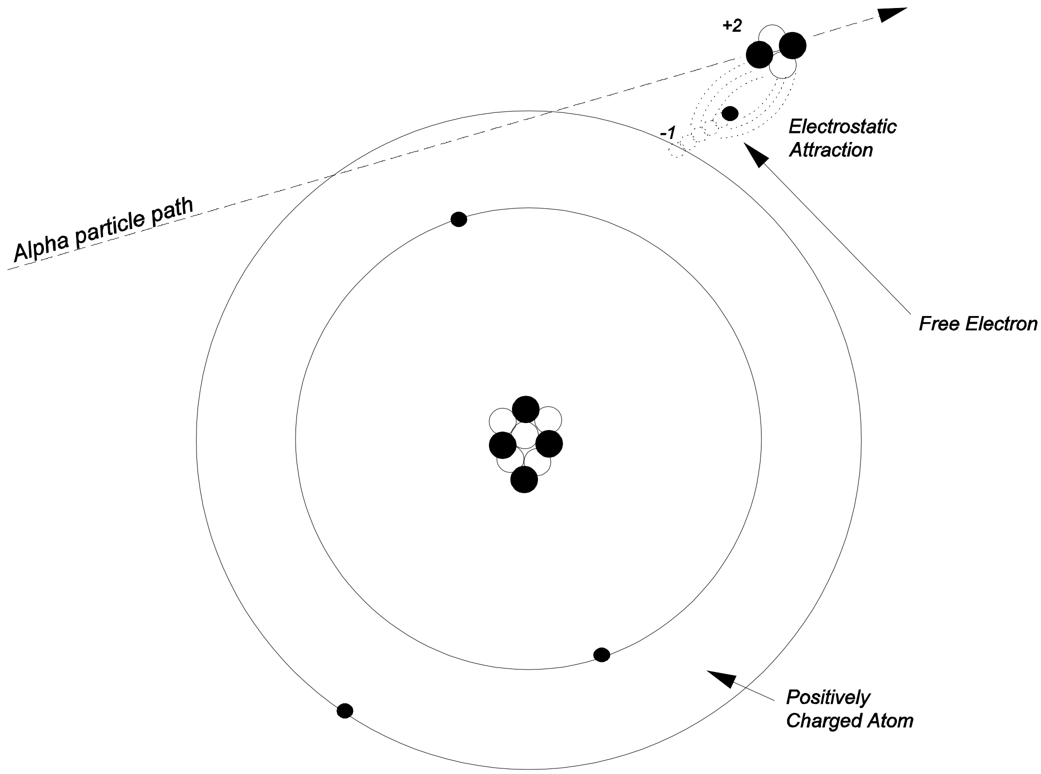

Figure 3 - Ionization by an Alpha Particle

1.07.03	*Identify the two major mechanisms of energy transfer for alpha particulate radiation.*

Alpha collisions may result in energy transfer by 1) ionization and/or 2) excitation. And since a finite amount of energy is required to ionize or excite an atom, the kinetic energy of the alpha particle is gradually dissipated by such interactions until it captures two electrons and settles down to a quiet existence as a helium atom. Since the average amount of energy to ionize most materials is much less than the initial energy of most alpha particles, many ionizations will occur before the alpha particle is stopped.

Due to the high probability of interaction between an alpha particle and the orbital electrons of the absorbing medium and because of the +2 charge, a large number of ion pairs are formed per unit path length. Therefore, this type of radiation loses its energy over a relatively short distance. For these reasons, the range of alpha particles is much less than the range of other forms of radiation. It is, in summary, a highly ionizing, weakly penetrating radiation.

Alpha particles from a given radionuclide are all emitted with the same energy, consequently those emitted from a given source will have approximately the same range in a given material. Alpha particle range is usually expressed in centimeters of air. The relationship between range and energy has been expressed empirically as follows:

$$\mathbf{R_a = 0.318\ E^{3/2}}$$

where:

$\mathbf{R_a}$ = Range in cm of air at 1 atmosphere and 15 °C
E = Energy in MeV.

As stated above, the number of ion pairs formed per centimeter of path in any given medium is called the specific ionization for that particular ionizing radiation.

$$\text{Specific ionization} = \frac{\text{number of ion pairs formed}}{\text{Centimeter of path length}}$$

On average, approximately 34 electron volts of energy is lost for each primary ion pair formed in air. Only about half to two-thirds of this energy is actually required to remove the orbital electron, the balance being lost in electronic excitation processes. Depending on the energy of the alpha particle, the number of ion pairs formed per centimeter of path in air will range from 5,000 to 80,000.

BETA ABSORPTION

A beta particle is a free (unbound) electron with kinetic energy (e.g. a moving electron). Therefore, the rest mass and charge of a beta particle are the same as that of an orbital electron. The negatively charged electron has an anti-particle which has the same mass but a positive charge called a positron. Their masses are very much smaller than the mass of the nuclei of the atoms making up the absorbing medium. An interaction between a positively charged beta particle or a negatively charged beta particle and an orbital electron is therefore an interaction between two charged particles of similar mass. Negatively charged beta particles and orbital electrons have like charges; therefore, they experience an electrostatic repulsion when in the vicinity of one another. Positively charged beta particles and orbital electrons have unlike charges, so they experience an electrostatic attraction when in the vicinity of one another.

Because the rest masses are equal, the interaction between either of these two beta particles and an orbital electron is similar to the collision between billiard balls. Therefore, a beta particle may lose all of its energy in a single collision. In such an interaction, the target electron acquires such high kinetic energy it becomes a particle similar to the beta particle.

Normally, however, a beta particle of either charge loses its energy in a large number of ionization and excitation events in a manner analogous to the alpha particle. Due to the smaller size and charge of the electron, however, there is a lower probability of beta radiation interacting in a given medium; consequently, the range of a beta particle is considerably greater than an alpha particle of comparable energy.

A negatively charged beta particle has a charge opposite to that of the atomic nucleus, therefore an electrostatic attraction will be experienced as the beta approaches the nucleus. A positively charged beta particle has a charge the same as that of the atomic nucleus, therefore an electrostatic repulsion will be experienced as the beta approaches the nucleus. Since the mass of either particle is small compared with that of a nucleus, large deflections of the beta can occur in such collisions, particularly when electrons of low energies are scattered by high atomic number elements (high positive charge on the nucleus). As a result, a beta particle usually travels a tortuous, winding path in an absorbing medium.

1.07.04 *Identify the three major mechanisms of energy transfer for beta particulate radiation.*

Like an alpha particle, a beta particle may transfer energy through ionization and excitation. In addition, a beta may have a Bremsstrahlung interaction with an atom which results in the production of X-rays. Figure 4 below schematically shows a Bremsstrahlung interaction. In this case, a high energy beta penetrates the electron cloud surrounding the nucleus of the atom, and experiences the strong electrostatic attractive force of the positively charged nucleus. This results in a change in velocity/kinetic energy of the particle and the emission of a Bremsstrahlung X-ray.

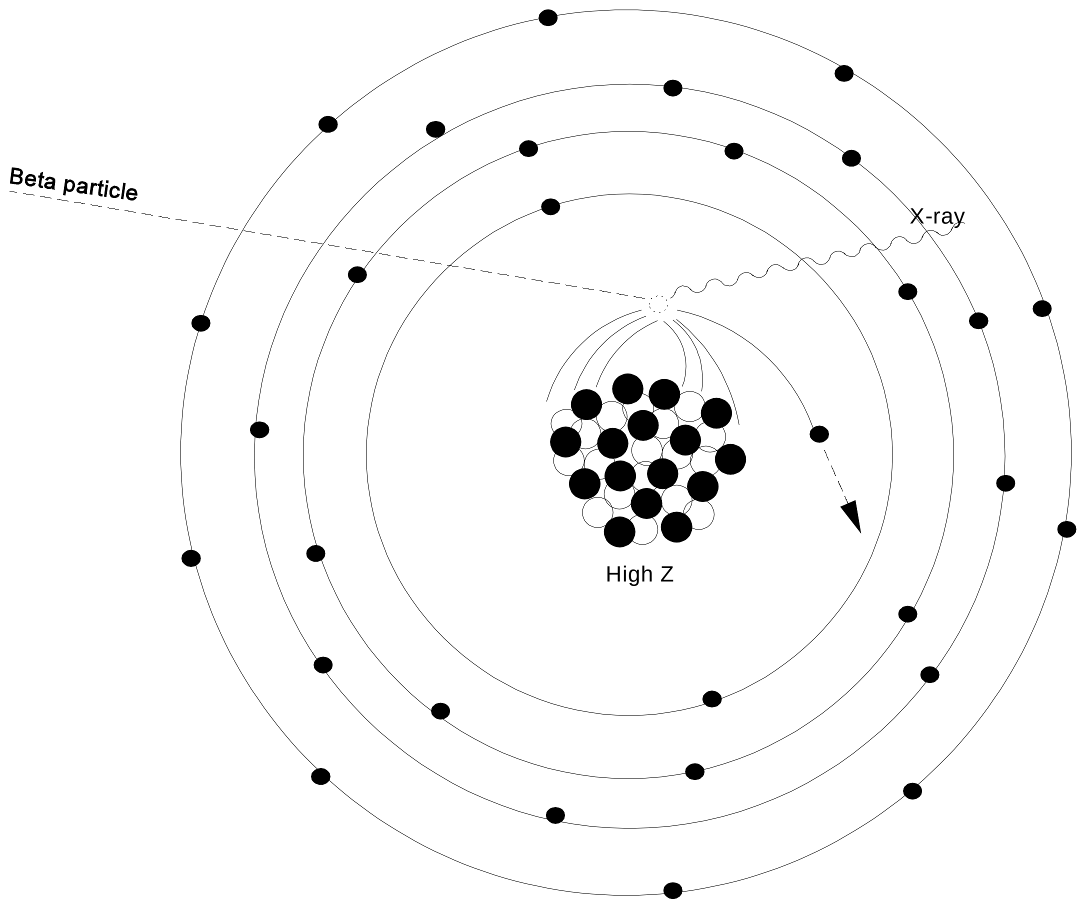

Figure 4 - Bremsstrahlung Radiation

The energy of the X-ray emitted depends on how much deflection of the beta particle occurred, which in turn, depends on how close the electron came to the nucleus. Therefore, a spectrum of different energy X-rays are observed from the many different Bremsstrahlung encounters an electron will have before it loses all of its energy. Because it is much less likely for a close encounter with the nucleus than a distant encounter, there are more low energy X-rays than high energy X-rays (maximum energy is the energy of the beta particle). Bremsstrahlung becomes an increasingly important mechanism of energy loss as the initial energy of the beta increases, and the atomic number of the absorbing medium increases.

Beta particles resulting from radioactive decay may be emitted with an energy varying from practically zero up to a maximum energy. Each beta particle will have a range in an absorber based on its energy. After entering a medium, there will be beta particles with different energies. Therefore, determining the number of beta particles found at a given depth in an absorber and the number of X-rays produced is complex and a function of the energy distribution of the beta particles.

INDIRECTLY IONIZING RADIATION

The types of radiation that have no charge (electromagnetic radiation and neutrons) have no coulomb force field extending beyond their physical dimensions to interact with the fundamental particles of matter. They must come sufficiently close and their physical dimensions contact these particles in order to interact. Radiation and neutrons have physical dimensions much smaller than atomic dimensions. They, therefore, move freely through the largely empty space of matter and have a small probability of interacting with matter. In contrast to directly ionizing radiation described above, uncharged radiation does not continuously lose energy by constantly interacting with the absorber. Instead, it may penetrate material and move "through" many atoms or molecules before its physical dimension contacts that of an electron or nucleus. Indeed, in a chest X-ray, the image is the distribution of X-rays that made it to the film without interacting in the patient's chest. This type of radiation is called indirectly ionizing radiation. The probability of interaction is dependent upon the energy of the radiation and the density and atomic number of the absorber. When indirectly ionization particles do interact, they produce directly ionizing particles (charged particles) that cause secondary ionizations.

GAMMA ABSORPTION

X- and gamma rays differ only in their origin, and an individual X-ray could not be distinguished from an individual gamma ray. Both are electromagnetic waves, and differ from radio waves and visible light waves only in having much shorter wavelengths. The difference in name is used to indicate a different source: gamma rays are of nuclear origin, while X-rays are of extra-nuclear origin (i.e., they originate in the electron cloud surrounding the nucleus). Both X-rays and gamma rays have zero rest mass, no net electrical charge, and travel at the speed of light. They are basically only distortions in the electromagnetic field of space, and can be viewed as packets of energy (quanta) that interact with atoms to produce ionization even though they themselves possess no net electrical charge. As previously pointed out, gamma rays will be discussed as the prototype of this type of radiation.

1.07.05	*Identify the three major mechanisms by which gamma photon radiation interacts with matter.*

There are three major mechanisms by which gamma rays lose energy by interacting with matter.

The Photoelectric Effect

The photoelectric effect (first mechanism) is an all-or-none energy loss. The photon imparts all of its energy to an orbital electron of some atom. The photon, since it consisted only of energy in the first place, simply vanishes. The photoelectric effect is only significant for initial photon energies less than 1 MeV. Figure 5 below schematically shows a photoelectric interaction. The energy is imparted to the orbital electron in the form of kinetic energy of motion, overcoming the attractive force of the nucleus for the electron (the binding energy) and usually causing the electron to leave its orbit with considerable velocity. Thus, an ion-pair results.

The high velocity electron, which is called a photoelectron, is a directly ionizing particle and typically has sufficient energy to knock other electrons from the orbits of other atoms, and it goes on its way producing secondary ion-pairs until all of its energy is expended. The probability of photoelectric effect is maximum when the energy of the photon (gamma) is equal to the binding energy of the electron. The tighter an electron is bound to the nucleus, the higher the probability of photoelectric effect so most photoelectrons are inner-shell electrons. The photoelectric effect is seen primarily as an effect of low energy photons with energies near the electron binding energies of materials and high Z materials whose inner-shell electrons have high binding energies.

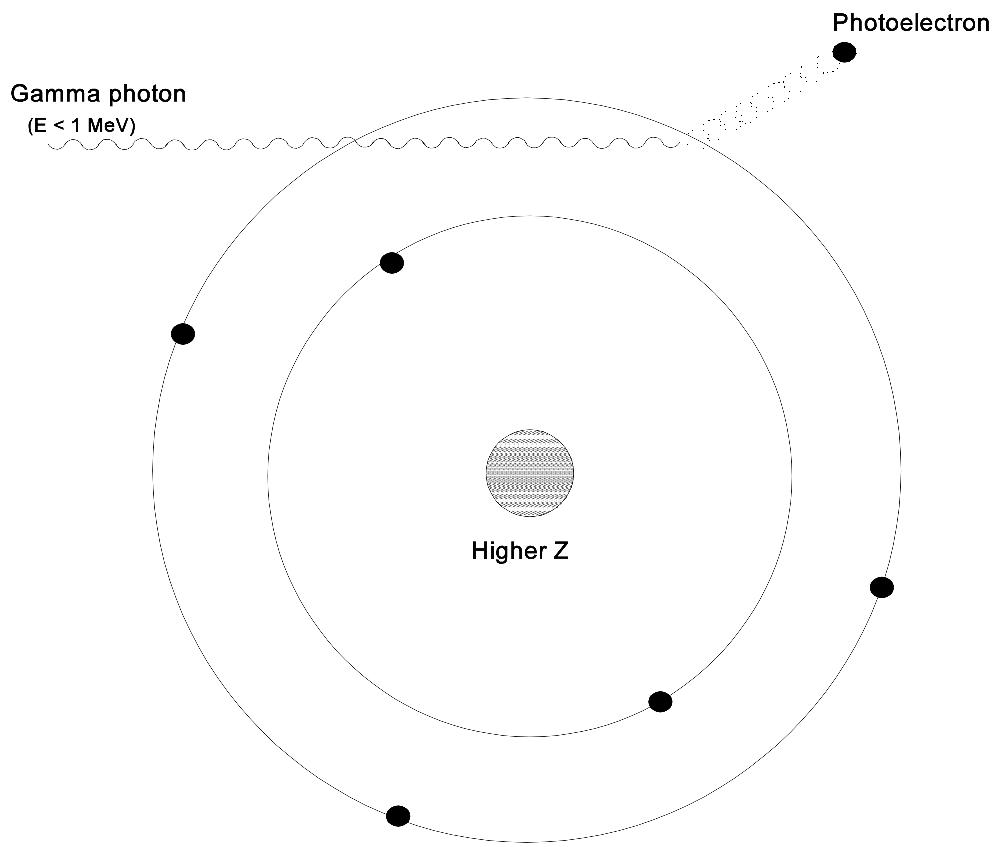

Figure 5 - Photoelectric Effect

Compton Scattering

In Compton scattering (the second mechanism) there is a partial energy loss for the incoming photon. The photon interacts with an orbital electron of some atom and only part of the energy is transferred to the electron. Compton scattering is the dominant interaction for most materials for photon energies between 200 keV and 5 MeV. Figure 6 below schematically shows a Compton interaction also called Compton scattering.

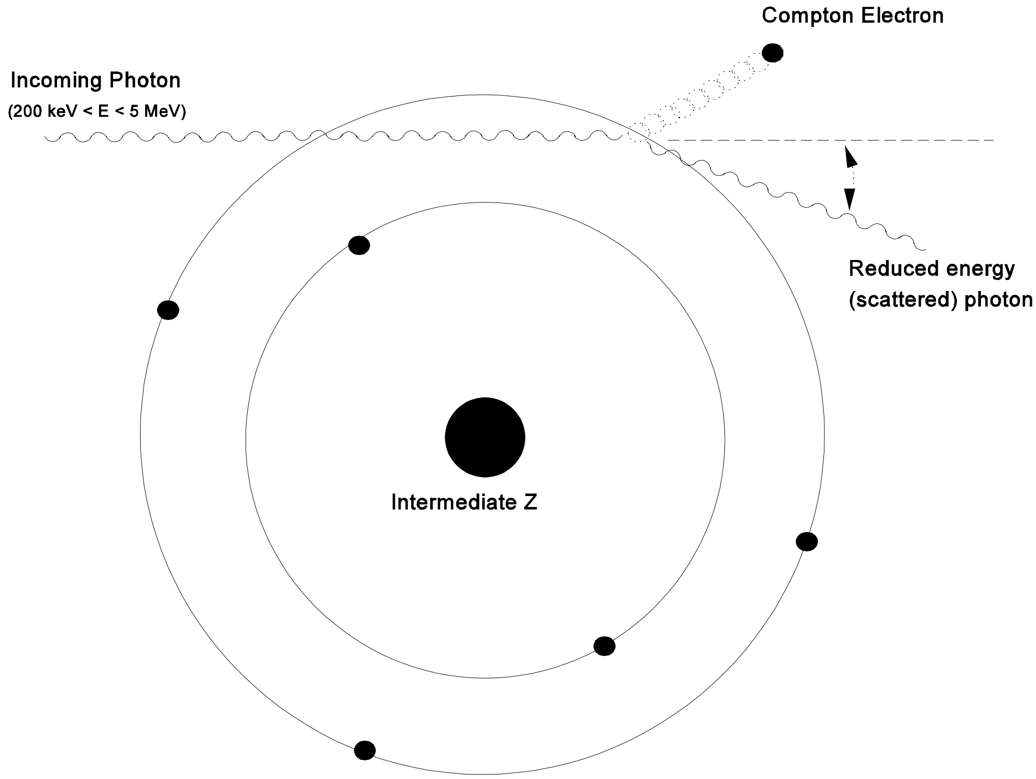

Figure 6 - Compton Scattering

A photon continues on with less energy and in a different direction to conserve momentum in the collision. The high velocity electron, now referred to as a Compton electron, produces secondary ionization in the same manner as does the photoelectron, and the "scattered" photon continues on until it loses more energy in another photon interaction. By this mechanism of interaction, photons in a beam may be randomized in direction and energy, so that scattered radiation may appear around corners and behind shields where there is no direct line of sight to the source. The probability of a Compton interaction increases for loosely bound electrons. Therefore, most Compton electrons are valence electrons. Compton scattering is primarily seen as an effect of medium energy photons.

Pair Production

Pair production (the third mechanism) occurs when all of energy of the photon is converted to mass. This conversion of energy to mass only occurs in the presence of a strong electric field, which can be viewed as a catalyst. Such strong electric fields are found near the nucleus of atoms and is stronger for high Z materials. Figure 7 below schematically shows pair production and the fate of the positron when it combines with an electron (its anti-particle) at the end of its path.

In pair production a gamma photon simply disappears in the vicinity of a nucleus, and in its place appears a pair of electrons: one negatively charged and one positively charged. These anti-particles are also called an electron and a positron respectively. The mass of these electrons has been created from the pure energy of the photon, according to the familiar Einstein equation $E = mc^2$, where (E) is energy in joules, (m) is mass in kilograms, and (c) is the velocity of light in m/sec. **Pair production is impossible unless the gamma ray possesses greater than 1.022 MeV of energy to make up the rest mass of the particles.** Practically speaking, it does not become important until 2 MeV or more of energy is possessed by the incident photon.

Any excess energy in the photon above the 1.022 MeV required to create the two electron masses, is simply shared between the two electrons as kinetic energy of motion, and they fly out of the atom with great velocity. The probability of pair production is lower than photoelectric and Compton interactions because the photon must be close to the nucleus. The probability increases for high Z materials and high energies.

The negative electron behaves in the same way as any electron with kinetic energy, producing secondary ion-pairs until it loses all of its energy of motion. The positive electron (positron) also produces secondary ionization as long as it is in motion, but when it has lost its energy and slowed almost to a stop, it encounters a free (negative) electron somewhere in the material. The two are attracted by their opposite charges, and upon contact, because they are antiparticles, they annihilate each other, converting the mass of each back into pure energy. Thus, two gamma rays of 0.511 MeV each arise at the site of the annihilation (accounting for the rest mass of the particles). The ultimate fate of the "annihilation gammas" is either photoelectric absorption or Compton scattering followed by photoelectric absorption.

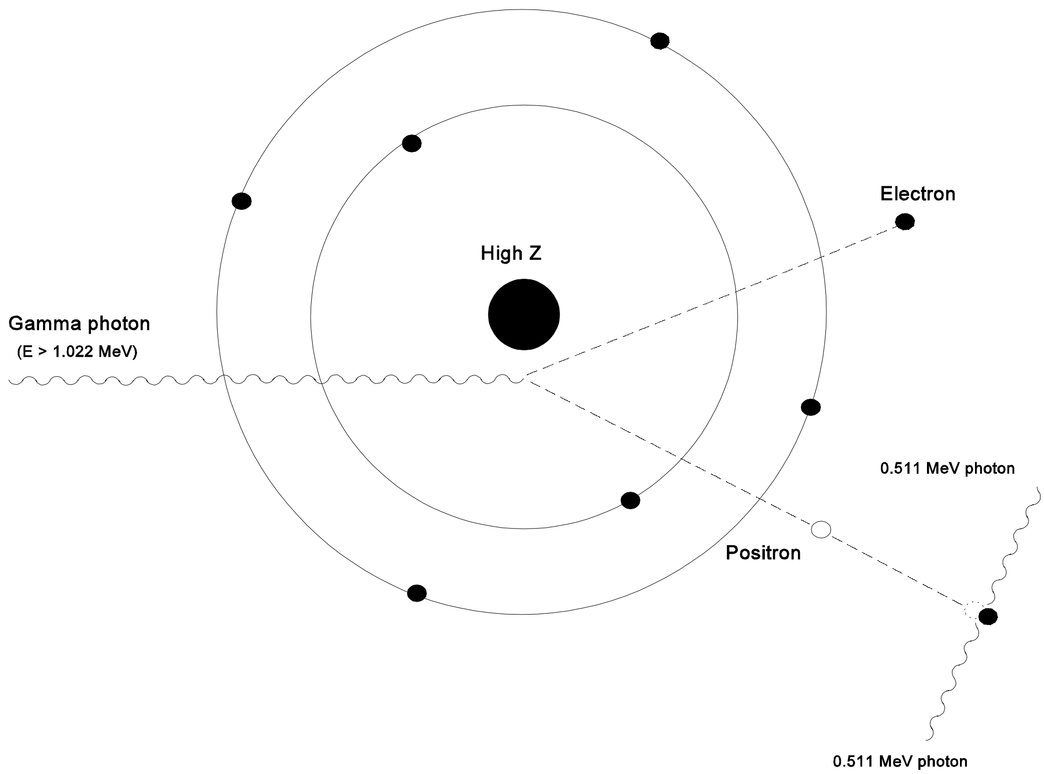

Figure 7 - Pair Production and Annihilation

NEUTRON INTERACTIONS

The neutron has a mass number of 1 and no charge. Because it has no charge the neutron can penetrate relatively easily into a nucleus. Free unbound neutrons are unstable (radioactive) and disintegrate by beta emission with a half-life of approximately 10.6 minutes. The resultant decay product is a proton which eventually combines with a free electron (not necessarily the beta particle) to become a hydrogen atom.

During the time when free neutrons exist, they can interact with the material they are in (primarily with nuclei) and lose energy. Neutron interactions with the nucleus are very energy dependent so neutrons are classified on the basis of their kinetic energies. When a neutron is in "thermal equilibrium" with a material, it has kinetic energies appropriate for the kinetic energies of the atoms of the material. The most probable velocity of free neutrons in various substances at room temperature is approximately 2,200 meters per second. Their kinetic energy may be calculated from the equation:

$$\mathbf{E = 1/2mv^2}$$

where:

E = kinetic energy
m = Neutron mass in grams
v = Neutron velocity in cm/sec.

substituting:

$$E = \frac{1}{2} \text{ x } 1.66\text{E}-24 \text{ gm x } \left(\frac{2.2\text{E}5 \text{ cm}}{\text{sec}}\right)^2$$

$$E = 4.02\text{E}-14 \text{ gm}-\text{cm}^2/\text{sec}^2 \Rightarrow \text{ergs}$$

Since: 1 erg = 6.24E11 eV

$$E = [4.02\text{E}-14 \text{ ergs}] \left[\frac{6.24\text{E}11 \text{ eV}}{1 \text{ erg}}\right]$$

$$E = 0.025 \text{ eV.}$$

Neutrons with this average kinetic energy at 20 °C are called thermal neutrons.

1.07.06	*Identify the four main categories of neutrons as they are classified by kinetic energy for interaction in tissue.*

When neutrons are classified by their kinetic energies into various categories, frequently the energy ranges and names given to each neutron energy range is determined by the materials being used or research being conducted. For example, reactor physics, weapons physics, accelerator physics, and radiobiology each have generated a classification system that serves their needs. Typically the only category common to them all is thermal. The classification used for neutron interaction in tissue is important in radiation dosimetry and is shown in Table 2 below.

Table 2. Neutron Energy Categories

Category	Energy Range
Thermal	~ 0.025 eV ($\lesssim$ 0.5 eV)
Intermediate	0.5 eV - 100 keV
Fast	100 keV - 20 MeV
Relativistic	> 20 MeV

One should be familiar with the classification of neutrons by energy that applies to the area where they are working so no confusion arises when using terminology. For the remainder of this discussion, neutrons $\lesssim$ 2 keV will be called "slow neutrons" and neutrons $\gtrsim$ 2 keV will be called "fast neutrons." These are intended to be general references and do not correspond to specific energy ranges that are used in any specific discipline.

Classification of neutrons according to kinetic energy is important from two standpoints: (a) the interaction of neutrons with the nuclei of atoms differs with the neutron energy, and (b) the methods of producing, detecting and shielding against the various classes of neutrons are different.

Detection of neutrons is relatively difficult, due to the lack of ionization along their paths; negligible response to externally applied electric, magnetic or gravitational fields; and the fact that they interact primarily with atomic nuclei, which are exceedingly small.

Neutron Reactions

When describing neutron reactions with a nucleus, the standard notation is (n,Y) where n is the initial neutron and Y is the resulting emissions following the interaction with the nucleus.

1.07.07	*Identify three possible results of neutron capture for slow neutrons.*

Radiative capture with gamma emission is the most common type of reaction for slow neutrons. This (n,γ) reaction often results in product nuclei which are radioactive. For example:

$$^{59}_{27}\mathbf{Co} + {}^{1}_{0}\mathbf{n}\text{---->}{}^{60}_{27}\mathbf{Co} + \boldsymbol{\gamma}$$

This process of converting a stable nucleus to its radioactive counterpart by neutron bombardment is called "neutron activation." Many radionuclides used in nuclear medicine are produced by this process.

A second type of general reaction for slow neutrons is that giving rise to charged particle emission. Typical examples include (n,p), (n,d), and (n,α) reactions, i.e., reactions in which a proton, a deuteron, or an alpha particle is ejected from the target nucleus.

A third type of neutron-induced nuclear reaction is fission. Typically, fission occurs following the absorption of a slow neutron by several of the very heavy elements. When ^{235}U nuclei undergo fission by neutrons, an average of 2 to 3 neutrons are expelled along with associated gamma radiation. The nucleus splits into two smaller nuclei which are called primary fission products or fission fragments. These products usually undergo radioactive decay to form secondary fission product nuclei. As an example, if one neutron fissions a ^{235}U nucleus, it could yield yttrium-95, iodine-139, two neutrons and fission energy. There are some 30 different ways that fission may take place with the production of about 60 primary fission fragments. These fragments and the atoms which result from their decay are referred to as fission products, and they number between 400 and 600, according to the type and number of nucleons their nuclei possess.

Many fission products have found application in medicine, industry, and research. A well known example is ^{131}I which is used extensively in medicine as both a diagnostic and therapeutic agent.

The fission process is the source of energy for nuclear reactors and some types of nuclear weapons. Also, neutrons generated from the fissioning of the fuel in a reactor are used to activate stable materials to a radioactive form as previously discussed. Many radioisotopes used in medicine are produced by neutron activation in this manner.

Elastic and Inelastic Scattering

Neutron scattering is a fourth type of interaction with the nucleus. This description is generally used when the original free neutron continues to be a free neutron following the interaction. Scattering is the dominant process for fast neutrons when the neutron is moving too fast to become absorbed by a nucleus. Multiple scattering by a neutron is the mechanism of slowing down or "moderating" fast neutrons to thermal energies. This process is sometimes called "thermalizing" fast neutrons.

1.07.08 Identify elastic and inelastic scattering interactions for fast neutrons.

Elastic scattering occurs when a neutron strikes a nucleus (typically of approximately the same mass as that of the neutron) as schematically shown in Figure 8. Depending on the size of the nucleus, the neutron can transfer much of its kinetic energy to that nucleus which recoils off with the energy lost by the neutron. Hydrogen causes the greatest energy loss to the neutron because the single proton in the nucleus is approximately the same mass as the neutron. The process is analogous to the rapid dissipation of the energy of a cue ball when it hits another ball of equal mass on a billiard table. During elastic scattering reactions, it is worth noting, no gamma radiation is given off by the nucleus. The recoil nucleus can be knocked away from its electrons and, being positively charged, can cause ionization and excitation.

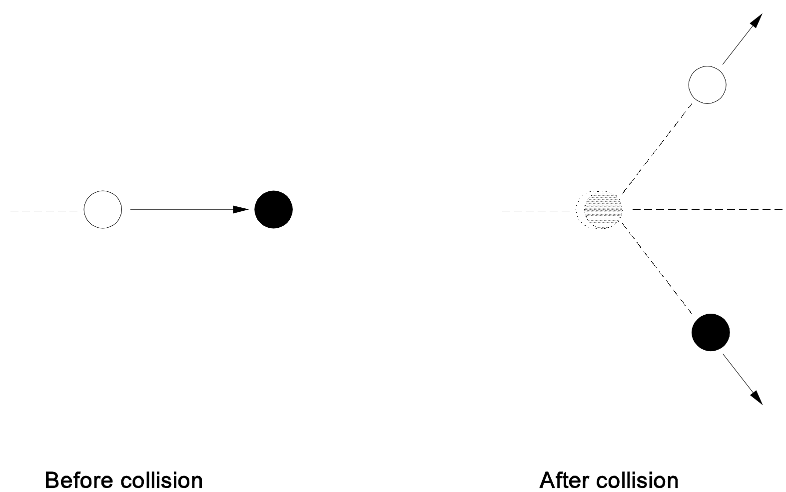

Figure 8 - Elastic Scattering

Inelastic scattering occurs when a neutron strikes a large nucleus as schematically shown in Figure 9 below. The neutron penetrates the nucleus for a short period of time, transfers energy to a nucleon inside, and then exits with a small decrease in energy. The nucleus is left in an excited state, emitting gamma radiation which can cause ionization and/or excitation.

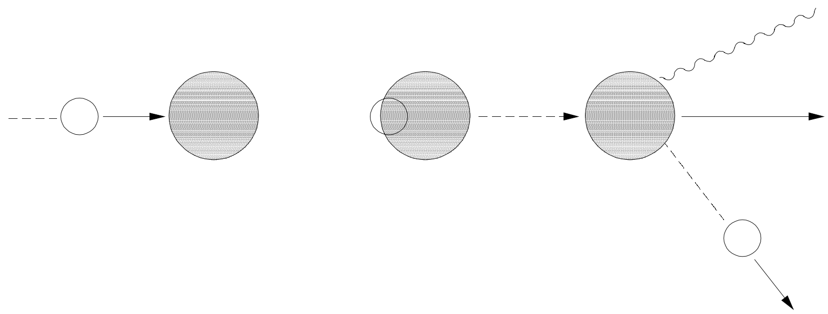

Figure 9 - Inelastic Scattering

Reactions in Biological Systems:

Fast neutrons lose energy in soft tissue mainly by repeated scattering interactions with hydrogen nuclei. The hydrogen nuclei are themselves scattered in the process. The scattered hydrogen nuclei have been "knocked" free of their electron and are thus moving protons (called recoil protons) which cause ionization.

Slow neutrons are captured in soft tissue and release energy by two principal mechanisms:

$$ {}^{1}_{0}\mathbf{n} + {}^{1}_{1}\mathbf{H} \rightarrow {}^{2}_{1}\mathbf{H} + \boldsymbol{\gamma} \text{ (2.2 MeV)} $$

and

$$ {}^{1}_{0}\mathbf{n} + {}^{14}_{7}\mathbf{N} \rightarrow {}^{14}_{6}\mathbf{C} + {}^{1}_{1}\mathbf{p} \text{ (0.66 MeV)} $$

The gamma and proton energies may be absorbed in the tissue and cause damage that can result in deleterious effects. This will be discussed in lesson 1.08.

Whenever charged particles, neutrons or photons are able to penetrate the nucleus and have sufficient energy, transmutations may be caused which often result in radioactivity. The bombarding projectile can be a neutron, proton, deuteron, alpha particle, electron, or gamma photon. Such bombarding particles may originate from other transmutations, radioactive decay, fission, fusion, or particle accelerators. As a result of the interaction of the projectile and target, a compound nucleus is formed, exists for an instant, (10E-12 sec), and then separates into a product particle or particles and product nucleus. Three laws govern these reactions: (1) conservation of mass number; (2) conservation of atomic number; and (3) conservation of total energy.

RADIATION SHIELDING

Introduction. Shielding is an important principle for radiological control. In this section, the basic principles for protection of personnel from the three major types of penetrating ionizing radiation (γ, β, neutron) are discussed. These principles are applicable regardless of types or energy of the radiation. However, the applications of the principles will vary quantitatively, depending on type, intensity and energy of the radiation source, e.g., beta particles from radioactive materials will require a different amount of shielding than high speed electrons from a high energy particle accelerator. For directly ionizing particles, the application of these principles would reduce personnel exposure to zero, for indirectly ionizing radiation, the exposure can be minimized consistent with the ALARA philosophy (to be discussed in Lesson 1.10).

Shielding of photons. When shielding against X-rays and gamma rays, it is important to realize that photons are removed from the incoming beam on the basis of the probability of an interaction such as photoelectric effect, Compton scatter, or pair production. This process is called attenuation and can be described using the "linear attenuation coefficient", μ, which is the probability of an interaction per path length x through a material (typical units are $\frac{1}{cm}$ or cm^{-1}). The linear attenuation coefficient varies with photon energy, type of material, and physical density of material. Mathematically the attenuation of photons is given by:

$$I(x) = I_o e^{-\mu x}$$

where:

$I(x)$ = Radiation intensity exiting x thickness of material
I_o = Radiation intensity entering material
e = Base of natural logarithms (2.714......)
μ = Linear attenuation coefficient
x = Thickness of material.

This equation shows that the intensity is reduced exponentially with thickness and only approaches zero for large thicknesses. I(x) never actually equals zero. This is consistent with the notion that because X-rays and gamma rays interact based on probability, there is a finite (albeit small) probability that a gamma could penetrate through a thick shield without interacting. Shielding for X-rays and gamma rays then becomes an ALARA issue and not an issue of shielding to zero intensities.

The formula above is used to calculate the radiation intensity from a narrow beam behind a shield of thickness x, or to calculate the thickness of absorber necessary to reduce radiation intensity to a desired level. Tables and graphs are available which give values of μ determined experimentally for all radiation energies and many absorbing materials.

The larger the value of μ the greater the reduction in intensity for a given thickness of material. The fact that lead has a high μ for X- and gamma radiation is partially why it is widely used as a shielding material.

Although attenuation of the initial beam of photons occurs by photoelectric, Compton, and pair production interactions, additional photons can be produced by subsequent interactions (immediately in the case of Compton). If the beam is narrow, these additional photons are "randomized" and are no longer part of the narrow beam of radiation. If the beam is broad, photons can be "randomized" and scattered into the area one is trying to shield. The secondary photons are accounted for by a build up factor, B, in the attenuation equation as follows:

$$I = BI_0e^{-ux}$$

where B is the buildup factor. Tables of dose build-up factors (indicating that the increased radiation intensity is to be measured in terms of dose units) can be found in the Radiological Health Handbook.

The buildup is mostly due to scatter. Scattered radiation is present to some extent whenever an absorbing medium is in the path of radiation. The absorber then acts as a new source of radiation. Frequently, room walls, the floor, and other solid objects are near enough to a source of radiation to make scatter appreciable. When a point source is used under these conditions, the inverse square law is no longer completely valid for computing radiation intensity at a distance. Measurement of the radiation is then necessary to determine the potential exposure at any point.

In summarizing shielding of photons the important considerations are:

- That persons in the area behind a shield where there is no direct line of sight to the source are not necessarily adequately protected.
- That a wall or partition is not necessarily a "safe" shield for persons on the other side.
- That in effect, radiation can be deflected around corners"; i.e., it can be scattered.

Shielding will also attenuate beta radiation, and it takes relatively little shielding to absorb it completely (i.e. the particle's range is less than the thickness of the material). Therefore, the general practice is to use enough shielding for complete absorption. For low energy beta emitters in solution, the glass container generally gives complete absorption. In many cases plastic shielding is effective and convenient.

The absorption of great intensities of beta radiation results in the production of Bremsstrahlung radiation. Since Bremsstrahlung production is enhanced by high Z materials, for effective shielding of beta particles one would use a low Z material, such as plastic. This would allow the Beta particle to lose its energy with minimal Bremsstrahlung production. A material suitable to shield the Bremsstrahlung X-rays (such as lead) would then be placed on the "downstream" side of the plastic. If low density and low Z number material (i.e., aluminum, rubber, plastic, etc.) is used for shielding beta particles most Bremsstrahlung can be avoided.

Tables and graphs are available which give the maximum range of beta particles of various energies in different absorbing media. These can be used for calculation of the shielding necessary for protection against beta radiation.

Fast neutrons are poorly absorbed by most materials and the neutrons merely scatter through the material. For efficient shielding of fast neutrons, one needs to slow them down and then provide a material that readily absorbs slow neutrons.

Since the greatest transfer of energy takes place in collisions between particles of equal mass, hydrogenous materials are most effective for slowing down fast neutrons. Water, paraffin, and concrete are all rich in hydrogen, and thus important in neutron shielding. Once the neutrons have been reduced in energy, typically either boron or cadmium are used to absorb the slow neutrons.

Borated polyethylene is commonly available for shielding of fast neutrons. Polyethylene is rich in hydrogen and boron is distributed, more or less, uniformly throughout the material to absorb the slowed neutrons that are available. When a boron atom captures a neutron, it emits an alpha particle, but because of the extremely short range of alpha particles, there is no additional hazard.

A shield using cadmium to absorb the slowed neutrons is usually built in a layered fashion because cadmium is a malleable metal that can be fashioned into thin sheets. Neutron capture by cadmium results in the emission of gamma radiation. Lead or a similar gamma absorber must be used as a shield against these gammas. A complete shield for a capsule type neutron source may consist of, first, a thick layer of paraffin to slow down the neutrons, then a surrounding layer of cadmium to absorb the slow neutrons, and finally, an outer layer of lead to absorb both the gammas produced in the cadmium and those emanating from the capsule.

Due to the relatively large mass and charge of alpha particles, they have very little penetrating power and are easily shielded by thin materials. Paper, unbroken dead layer of skin cells, or even a few centimeters of air will effectively shield alpha particles. The fact that alpha particles will not penetrate the unbroken dead layer of skin cells makes them primarily an external contamination problem and not an external dose problem. If alpha particles are allowed to be deposited internally, they become a very serious health hazard.

1.07.09 Identify the characteristics of materials best suited to shield:
a. alpha
b. beta
c. gamma
d. neutron radiations

Table 3. Shielding Material

Radiation	Typical Shielding Characteristics
alpha	thin amounts of most any material (paper, unbroken dead cell layer of skin, few cm of air)
beta	low Z and low density material (rubber, aluminum, plastic)
gamma	high Z and high density material (lead, depleted uranium)
neutron	hydrogenous material for moderation (oil, plastic, water) and capture material for absorption (boron, cadmium)

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